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Agricultural biogas plants in Poland: Investment process, economical and environmental aspects, biogas potential

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ABSTRACT

The formal and legal requirements as well as the support system for building agricultural biogas plants in Poland have been presented. There are currently 24 agricultural biogas plants operating in Poland. The fermentation substrates are slurry, food waste and maize silage. It is most often mesophilic fermentation. Produced biogas is combusted in cogeneration and thus obtained electrical and thermal energy is used for the biogas plant's own needs and sold. The support system for biogas plants' operation in Poland is based on a system of certificates. In this system it is cost-effective to use waste for fermentation whilst it is not cost-effective for a biogas plant to run on maize silage. It has been calculated that in Poland the theoretical annual biogas potential for cattle slurry is 3646 million m^3, for pig slurry it is 2581 million m^3, for poultry manure it is 717 million m^3, from maize after seed harvest it is 1044 million m^3, from municipal waste biofraction it is 100 million m^3 of biogas.

Contents

1. Introduction

The first historical records of using biogas for economic purposes occurred 3000 years ago in China [1–3]. Marco Polo also mentioned in his diary that biogas was produced in this area [4]. In 1895 biogas was used to power street lights in Exeter (UK) [5]. Many countries have been recently developing an energy sector based on biogas [6–9]. This has been influenced by both economic factors and care to protect the environment. High prices and limited resources of fossil fuels together with the technological progress and optimisation of the biogas production make biogas energy even cheaper. The use of biogas for energy production reduces the use of fossil fuels, the combustion of which contributes to the climate change [10,11].

The Polish energy sector has also noticed a possibility of biogas production, especially of agricultural biogas [12]. Agricultural biogas is at the moment a small fraction of Poland's general energy balance. However, the importance of biogas as an energy resource

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in Poland is increasing every year since Poland has a great biogas potential, which is comparable to that of Germany [8].

Experts are forecasting a dynamic development of agricultural biogas plants till 2020 at a rate of a few tens per cent a year [12–14].The highest amount of renewable energy obtained in Poland currently comes from solid biomass—85.4%, then from liquid biofuels—6.7%, from hydropower—3.6% and biogas—1.7% (Fig. 1) [15]. In the document "Energy Policy of Poland until 2030" [16], which was accepted by the Polish Government in 2009, the demand for the final biogas energy in Poland was summarically defined to be at the level of 35 PJ for electric and thermal energy.

The actual realisation of agricultural biogas potential in Poland during this period of time will depend on the effectiveness of the implementation of Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources [17]. The plan to implement the directive was presented in so called "National Renewable Energy Action Plan" [18]. It seems that in the coming years agricultural biogas will gain more significance on the green energy market and the growth rate will be among the highest in Europe.

2. Formal and legal requirements for the construction of an agricultural biogas plant in Poland

In Poland the definition of biogas is stipulated by the Energy Law of April 10 1997 [19]. According to this law, biogas is a gaseous fuel obtained as a result of methane fermentation of agricultural raw materials, agricultural by-products, liquid or solid animal faeces, by-products or residue from processing agricultural products or woodland biomass, excluding gas obtained from sewage treatment plants and waste dump sites.

Cogeneration is the most often method used to rewrite biogas in Poland for other useful forms of energy [20]. According to the Energy Law [19] cogeneration is defined as a simultaneous generation of heat and electrical or mechanical energy during the same technological process. The Energy Law [19] also defines how to calculate the amount of energy obtained from cogeneration. According to the Energy Law it is

(a) The total annual electrical power production at a cogeneration unit per calendar year, which was produced with the annual mean energy conversion efficiency of converting chemical energy of fuel into electrical or mechanical power and useful heat which is at least equal to the maximum efficiency:
- 75% for a cogeneration unit with such equipment as a back-pressure steam turbine, a gas turbine with heat recovery, a combustion engine, a microturbine, a stirling engine, a fuel cell, or
- 80% for a cogeneration unit with such equipment as a gas and steam system with heat recovery, a condensing and extraction steam turbine, or

(b) A product of the coefficient and the annual amount of useful heat in cogeneration, which was produced with the annual mean energy conversion efficiency of converting chemical energy of fuel into electrical or mechanical power and useful heat in cogeneration, which is lower than maximum efficiency mentioned in (a). This is calculated on the basis of a cogeneration unit's technological parameters measurements carried out over a given period of time. The coefficient defines the ratio of electrical power from cogeneration to useful heat in cogeneration [19].

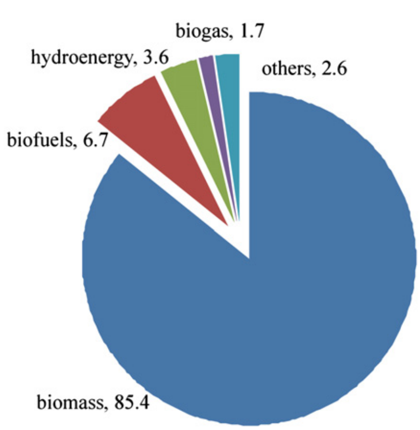

Fig. 1. Renewable energy balance for Poland in 2010 [15].

A certificate of the origin of agricultural biogas [21] confirms that agricultural biogas has been produced and has entered the gas distribution grid. The majority of waste suitable for methane fermentation is included in Council Directive 75/442/EEC of 15 July 1975 on waste [22], according to which biological fermentation is one of the possible methods of organic waste processing. It is worth mentioning that the Polish Law on Waste of 27 April 2001 [23] implements the guidelines of the Council within this context.

2.1. Project implementation

The investment process of agricultural biogas plants in Poland is very long. A Gantt chart shown in Fig. 2 is based on the legal requirements (deadlines that decision authorities need to adhere to) and the previous investment experience [24]. The time needed to prepare the project documentation, to obtain decisions and permits and to finalise the contract was about 2 years. Another year is needed for the project implementation as well as a biogas plant start-up and receipt.

The construction and operation of agricultural biogas plants should not exert a negative influence on the natural environment. Therefore, by means of consultation with local communities, a report to assess a biogas plant's impact on the natural environment is prepared. The course of action to be taken whilst preparing an assessment of the environmental impact in Poland is regulated by the Act of 3 October 2008 on the Provision of Information on the Environment and Its Protection, Public Participation in the Environmental Protection and Environmental Impact Assessments [25].

The Ordinance of Ministry of Agriculture and Food Industry of 7 October 1997 on technical conditions that should be met by agricultural buildings and their location stipulates [26] that biogas containers and fermentation chambers of volume up to 100 m^3 should be located at a distance of at least:

- 15 m: from windows and doors of occupied space and also from livestock buildings,
- 8 m: from other buildings,
- 5 m: from the boundary with the adjacent plot,
- 15 m: from coal and coke depot,
- 15 m: from other fermentation chambers and biogas containers,
- 15 m: from crops and fodder silos of volume bigger than 100*t*.

For biogas containers and fermentation chambers of volume exceeding 100 m^3 distance should be at least doubled [26].

Connecting a biogas plant to the energy system is regulated by the Energy Law and its executive acts [19]. According to the

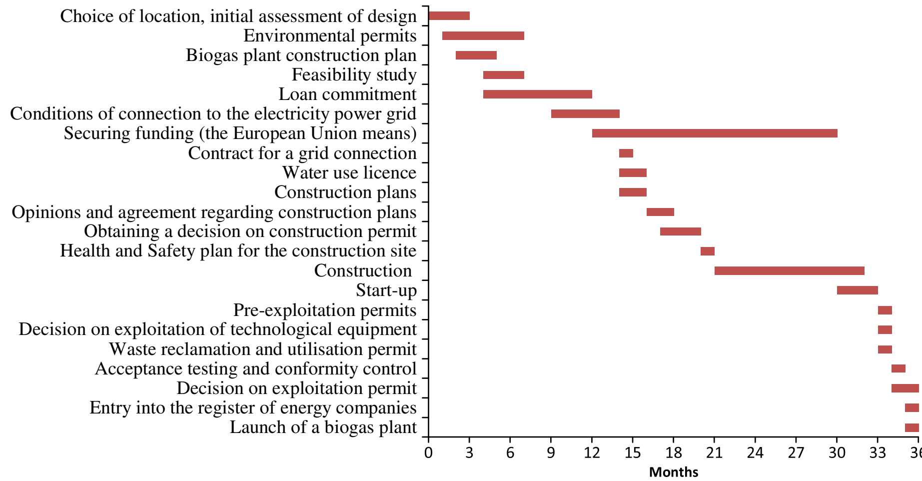

Fig. 2. Investment schedule of an agricultural biogas plant in Poland shown as a Gantt chart [24].

Table 1
Forms and sources of financing agricultural biogas plants depending on the legal status of a beneficiary [27–30].

Type of support	Beneficiary	Means						
		Domestic			Domestic and foreign			
		NFEP&WM	VFEP&WM	EPB	OPI&E	OP IE	REGIO	RDP
Loans, additional payments to loans	Local authorities	+	+	+				
	Entrepreneurs	+	+	+				
	Private individuals			+				
Grants	Local authorities		+	+	+	+	+	+
	Entrepreneurs	–	+	+	+	+	+	+
	Private individuals	–	–	–	–	–	–	+

NFEP&WM—The National Fund for Environmental Protection and Water Management, VFEP&WM—Voivodeship Funds for Environmental Protection and Water Management, EPB—Environmental Protection Bank, OPI&E—Operational Programme "Infrastructure and Environment", OP IE—Operational Programme "Innovative Economy", REGIO—Regional Operational Programme, RDP—Rural Development Programme.

Energy Law, a gas distribution system operator is obliged to receive agricultural biogas of quality parameters defined in executive acts to the Energy Law and produced in plants directly connected the grid of this operator [19].

2.2. *The support system for building biogas plants*

The source of funding for agricultural biogas plants in Poland includes grants, loans and additional payments to loans from the public and the European Union means, commercial bank loans as well as the own funds of project implementers. Many of the existing and currently constructed biogas plants in Poland would most likely have never been built without the financial support. The financial help depends on the status of a beneficiary (Table 1) [27–30].

Great opportunities to subsidise biogas projects are provided by the programme "*The Green Investment Scheme, Part 2—Agricultural Biogas Plants*" [28], which is being implemented by the National Fund for Environmental Protection and Water Management. This programme is aimed at business entities intending to implement a venture related to electrical power and heat production out of agricultural biogas as well as producing agricultural biogas in order to deliver it to a gas distribution network.

Another key programme within the National Fund for Environmental Protection and Water Management is "*Programme for Renewable Energy Enterprises and High Performance Cogeneration Units*" [29], which can be used to subsidise biogas plants by means of a low-interest loan. The following types of venture are included among many different kinds of investment that can be subsidised within the programme:

- investment, as a result of which electrical power or heat is produced using biogas obtained in a process of sewage discharge or treatment,
- investment, as a result of which electrical power or heat is produced using biogas obtained from decomposition of plant and animal remains, and
- investment related to the construction, extension or redevelopment of an agricultural biogas plant in order to deliver biogas to a gas distribution grid.

3. Agricultural biogas plants in Poland—the current state

The first biogas plant in Poland was opened in 1928 at the sewage treatment plant in Poznań [31]. After World War II agricultural mini biogas plants were created. For example, in Tworóg (located near Katowice) [32] there used to be a biogas plant where 5 m^3 of slurry per 24 h was treated and about 70 m^3 of biogas per 24 h was produced. The small-size biogas plants of that time quickly went bankrupt. Their operation often came to a standstill as a result of mistakes made during the construction stage and the methane fermentation method they used meant they were not cost-effective.

In Poland there are currently 178 biogas power plants in operation, the total power of which is 104 MW [33,34]. There are 87 landfill biogas plants (total power of 54 MW), 67 biogas plants located at the sewage treatment works (total power of 34 MW),

and 24 agricultural biogas plants (total power of 16 MW). It is worth pointing out that the 23 agricultural biogas plants in Poland have been constructed within the last four years (since 2008).

The agricultural biogas systems currently operating in Poland differ in terms of particular parts of the process line. This mostly depends on the specific local circumstances such as the type and properties of used substrates, the way biogas is used as well as methods of managing the post-fermentation load. Fig. 3 shows a schematic diagram of a typical biogas plant in Poland.

In Poland, like in the whole of Europe, it is mostly mesophilic fermentation (temperature 32–42 °C) that is carried out. It is only in the currently opening agricultural biogas plant in Mełno that biogas is going to be produced by means of thermophilic fermentation (50–57 °C) [35].

Biogas produced in a fermentation tank can be converted into energy or purified to the form of biomethane and sent to a gas distribution grid.

Biogas can be used to produce:

- electrical power in spark ignition engines or turbines,
- heat—in gas boilers,
- electrical power and heat—in cogeneration aggregates used for combined production of electrical power and heat, which is the most common method (and virtually the sole method) of using biogas for energy purposes in Poland [9].

The use of aggregates for the combined production of electrical power and heat ensures a higher efficiency of the whole system, which results in a more economical energy production. The efficiency of electricity production in the newest aggregates is within 35%–40%, whilst the efficiency of heat recovery is within 40%–45%, which means that the total efficiency of the fuel utilisation is about 75%–85% [36].

Agricultural biogas plants in Poland most often operate near large animal farms, using as their substrate the otherwise noxious waste of slurry and manure. Biogas production is a far better alternative to the commonly used method of waste utilisation (in Poland slurry and manure are directly sprayed onto the fields). The process of biogas generation results in sanitation, which prevents a risk of ground water contamination. Moreover, electrical power and heat is produced whilst the post-fermentation residue is used as a fertilizer [37–39].

Appendix A contains the most important parameters for the materials undergoing methane fermentation in Poland [5,37–39]. On the other hand, Appendix B contains a description of agricultural biogas plants that currently operate in Poland [33,34,40–45].

The largest numbers of agricultural biogas plants are located in the north-west of Poland (Fig. 4), the owner of which is a company called Poldandor S.A. The company owns 29 livestock farms where it is planning to construct even more biogas plants. Waste in the form of slurry is the main substrate for biogas plants located at livestock farms. The development of biogas plants in the NW part of Poland was also possible due to their highly competent workers as well as a favourable attitude of local authorities and community [35].

The capital expenditure of the first centralised agricultural biogas plant in Pawłówek in Poland reached 8 million PLN. The substrate for biogas production at the biogas plant in Pawłówko is slurry from the nearby farms in Pawłówko and Dobrzyń (about 29,000 Mg/year), maize silage and waste from the nearby slaughter houses (3500 Mg/year) which undergoes earlier sterilisation at a temperature of 70 °C as well as glycerol (1000 Mg/year). The plant in Pawłówek consists of two fermentation tanks, a mixing tank (preliminary), two post-fermentation tanks and a waste steriliser. Post-fermentation residue is carried to air-tight tanks and used as an organic fertliser. Electrical power obtained from biogas combustion is used for the plant's own needs (mixers, room lighting) and also sent to the power grid—the biogas plant

Fig. 4. Location of agricultural biogas plants as of March 2012 [33,34,40–45].

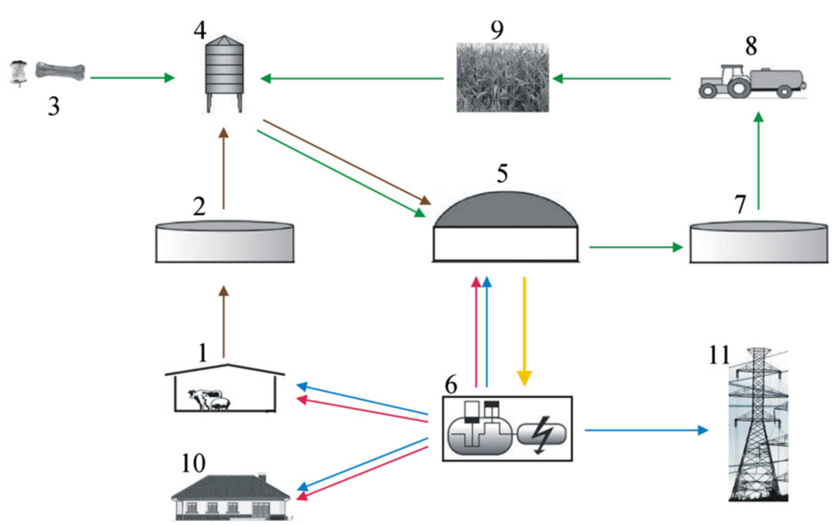

Fig. 3. A schematic diagram of a biogas plant. 1: cow shed/pigsty/hen house, 2: preliminary tank, 3: agricultural/slaughter waste, 4: mixing tank, 5: bioreactor, 6: cogeneration aggregate, 7: post-fermentation tank, 8: collection of post-fermentation fertiliser, 9: maize silage, 10: offices, and 11: energy distribution grid.

meets the power demand of almost 1800 individual households. Heat produced as a result of cogeneration is used to heat the farm and office buildings [24,40,41].

The two biggest agricultural biogas plants in Poland are located in Koczała and Liszkowo (Fig. 4). The plant in Koczała, which was constructed at a farm with 8000 sows, processes by means of fermentation 58,000 Mg of liquid manure and 32,000 Mg of maize silage. The correctly proportioned substrates are placed in a mixer and then are directed to the three fermentation tanks. Fermentated biomass is sent to the two post-fermentation tanks, where it is stored before being used for agricultural purposes. After sulphur compounds have been removed through a biological filter, biogas is sent to the cogeneration system. Electrical power and heat is used to meet the plant's own needs: at the plant itself, a feed mixing facility and the farm; any surplus energy is sold [24,42].

In Nacław (Fig. 4) a 1.5 km long heat network is being built, which will connect a biogas plant with six blocks of flats, a community centre and a school. The total heat produced by the biogas plant will meet the demand of a few hundred inhabitants. This will enable the two old coal and heating oil powered boilers to be switched off and will ensure that the inhabitants receive a steady supply of heat all year round [24,41].

Small, household agricultural biogas plants are also built in Poland. At a biogas plant in Szewnia (Fig. 4) 50 kg of field crops or their by-products (beetroot, cereals, straw, and leaves) is sent to the fermentation tank every 24 h. About 1 m^3 of biogas per hour is produced from this amount of biomass [44]. In Studzionka the following substrates are used: poultry manure (690 Mg/year), pig slurry (320 Mg/year), maize and grass silage (365 Mg/year) and, in small amount, agricultural production and household waste. Electrical power that is produced there is currently used to meet the needs of the biogas plant and the farm. Heat is used to heat house buildings as well as a pig stock building. Fermented slurry is used to fertilise fields [45].

4. Economic conditions for functioning of an agricultural biogas plant in Poland

One of the most important legal regulations on energy turnover in Poland is a requirement that companies dealing in electrical power and selling it to the final consumers are obliged to purchase electrical power from renewable sources [46]. If the requirement of presenting renewable energy source certificates for redemption is not met (or if a substitution fee has not been paid), then an energy company is subject to a penalty fee, which is not lower than 130% of a substitution fee determined for a given year by the Energy Regulatory Office. Therefore, a biogas plant can reap profits from selling electrical energy and heat as well as from certificates: a green one—a certificate of renewable energy source, a yellow one—a certificate of energy produced in cogeneration, a purple one—a certificate of methane combustion.

The biogas energy sector is supported by means of certification in Poland, Sweden and partly in Italy. In most countries the support system is based on guaranteed prices and long-term contracts. Germany, which is the leader of biogas use in Europe, apart from the stable, guaranteed prices, uses a system of numerous bonuses. These incentive payments include a bonus for using energy crops, a cogeneration bonus, a technological bonus, and, in case of biogas plants of power 0–500 kW, bonuses for using slurry and protecting the landscape or a formaldehyde bonus [6,32].

The basic economic profits for the biogas plant investors in Poland come from the income from selling the products generated during a plant's operation:

- produced electrical power as well as obtained certificates of origin,
- obtained surplus process heat,
- post-fermentation pulp in the form of a fertiliser, and
- payments for utilising noxious and organic waste.

Table 2 shows the income of a biogas plant of power of 1 MW_{el} and 1 MW_t depending on what was used as the main substrate (slurry, slaughter waste, maize silage, and organic municipal waste). The amount of biogas produced in this particular biogas plant is about 3.7 million m^3/yr. Assuming that the efficiency of electrical power production is at the level of 40% and that of heat is at the level of 45% and that 10% of produced electrical power and 25% of heat is used for the plant's own needs, the amount of electrical power that will be sold is at the level of 7.5 GWh_e/yr and that of heat

Table 2
Income and expenditure of an agricultural biogas plant **(own data based on Refs.** [24,27,39]**).**

Main substrate		Option 1 Slurry, 75,000 Mg	Option 2 Slaughter waste, 10,000 Mg	Option 3 Maize silage, 21,000 Mg	Option 4 Organic municipal waste, 42,000 Mg
Types of income	Income per unit	Annual income [million PLN]			
Electrical power sale	195 PLN[a]/MWh	1.46	1.46	1.46	1.46
Heat sale	38 PLN/GJ	0.96	0.96	0.96	0.96
Sale of green certificates	270 PLN/MWh	2.03	2.03	2.03	2.03
Sale of yellow certificates	127 PLN/MWh	0.95	0.95	0.95	0.95
Sale of purple certificates	59 PLN/MWh	0.44	0.44	0.44	0.44
Taking slaughter waste for utilisation	120 PLN/Mg	–	1.2	–	–
Fertiliser sale (40% of feedstock mass)	50 PLN/Mg	1.50	0.20	0.42	0.84
Income		7.34	7.24	6.26	6.68
Types of expenditure		Annual expenditure [million PLN]			
Purchase of substrates	130 PLN/Mg (maize)	–	–	2.73	
Annual cost of running a biogas plant (CHP service and maintenance, salaries, taxes, insurance)		4.00	4.00	4.00	4.00
Profit		3.34	4.06	−0.47	2.68

[a] 1 PLN = 0.31 USD = 0.24 EUR (18.04.2012.).

is at the level of 7 GWh_t/yr. As shown in Table 2 it was assumed that slurry and organic municipal waste would be given free of charge, utilisation of 1 Mg of slaughter waste would generate an income of 120 PLN/Mg, the cost of purchase (and storage) of maize silage would be 130 PLN/Mg. It was estimated that the annual cost of running a biogas plant would be at the level of 4 million PLN.

Analysing data presented in Table 2, it can be concluded that using animal or plant waste generates a profit at the level of 3–4 million PLN, whilst using solely maize bought at a commercial price leads to a loss. The sale of "colour" certificates results in an income of 3.42 million PLN, without which a biogas plant using only slaughter waste would just break an even. On the other hand, it should be remembered that both slurry and slaughter waste need to undergo utilisation, which is quite costly for farms and slaughter houses. Introducing even small fees for the utilisation of slurry and the organic fraction of municipal waste would significantly improve the economic situation of a biogas plant.

The cost of purchasing and storing maize silage is a considerable part of a biogas plant's expenditure. Operating costs (without depreciation) of a described biogas plant reach about 4 million PLN. This means that an agricultural utilisation biogas plant located next to a secure source of substrate produces a return on investment after a few years (Net Present Value $NPV > 0$).

The way particular types of capital investment expenditures are divided in terms of their components depends on a process design of a particular biogas plant. However, it is possible to identify certain significant and recurring types of investment expenditures. Two basic components seem to occur in all the analysed biogas plants: the construction of fermentation tanks and purchase of cogeneration aggregates. Percentagewise, these components constitute about 20% of capital investment expenditures each. The construction of other tanks (other than fermentation tanks) and of gas treatment plants as well as the purchase of technologies play a significant part in the costs too [47]. Capital investment expenditures needed to build a biogas plant of power of 1 MW_{el} and 1 MW_t reach about 12–13 million PLN [27].

When estimating economic profits, it is important to remember other more difficult to measure, intangible benefits. The location of biogas plants near prospective customers reduces the network loss of sent energy. In addition, creating sources of distributed energy postpones the need to extend transport and distribution grids. The local community can utilise noxious waste, new jobs are created and the local community and district receive an income from business activity taxation and can use cheaper energy (especially heat) from an independent source [48,49].

5. Environmental and ecological aspects of functioning of an agricultural biogas plant

The most important environmental benefits of agricultural biogas utilisation in Poland include:

- reduction in CO_2 emission from conventional fuels' combustion,
- reduction in CH_4 emission from the natural decomposition of organic substances,
- increased energy efficiency due to cogeneration (more efficient use of fuel),
- an energy sector based on biogas is a distributed one due to which network losses on sent energy are avoided (they reach 40% in Poland),
- a sanitary aspect.

In Poland, where electrical power and heat is obtained from hard coal and brown coal, the production of 1 MWh of energy in power plants leads to the emission of about 820 kg CO_2, 1.9 kg SO_2, 0.17 kg CO and 0.12 kg of dusts [50]. This means that the previously described biogas plant of power of 1 MW_{el} and 1 MW_t would lead to the following amounts of substances not being emitted to the atmosphere: 11890 Mg CO_2 (assuming there would be a closed circuit CO_2 for biogas), 27.5 Mg SO_2 (according to emission standards [51], the biogas plant emission is at the level of 100 kg), 2.5 Mg CO and 1.7 Mg of dusts [52]. It is worth noting that hard and brown coal is the most popular fuel used for heating homes in Poland, due to which in winter there is a rapid, uncontrolled increase of gas emission from burning these types of fuel in boilers without any filters [53].

Significant emission of acidic oxides, dusts and heavy metals, which is linked to hard and brown coal combustion in Poland, exerts a negative impact on the health of people and animals. The ash was found to contain an increased amount of radionuclides which increase risk of neoplastic lesions and genetic defects. Sulphur oxides as well as the acidity of rain lead to a faster wear of materials, especially steel, limestone and sandstone used in construction materials, mortar and paint [54]. The emission of greenhouse gases contributes to the climate change, which could adversely affect forestry management and agriculture, energy demand and water resources [55,56].

Also, the extraction of hard and brown coal has an associated negative environmental impact. It is particularly noticeable in case of brown coal where, as a result of mass coal extraction and transportation of great amount of overburden, large scale landscape development takes place. An outside spoil tip is created as well as a mining heading, located lower than the natural topography of the land. The area of an open-pit mine needs to be drained, which results in lowering of the ground water level and dying out of vegetation [57].

A biogas plant facilitates a controlled management of organic waste. As a result of the natural biomass decomposition processes, methane is created and released to the atmosphere contributing to the greenhouse effect. The use of non-fermented slurry and manure as fertilisers leads to considerable methane emission into the atmosphere. Obtaining methane by means of controlled fermentation in a biogas plant as well as its use in energy production means it is possible to partially avoid methane emission and the emission of other greenhouse gases, which are normally released during animal faeces' decomposition [58].

According to the data provided by the National Centre for Emission Balancing and Management [59], the biggest source of methane emission in Poland is agriculture—35.5%, which is followed by emission from municipal waste—21.6% of the total methane emission in Poland. Fig. 5 shows the changes in the indicator of CH_4 emission from animal manure for cows and the other cattle between 1990 and 2009. A rise in emission from the late 1990s is caused by an increase in the intensive livestock rearing system and feeding high energy fodder. Cows are intensively fed highly caloric cereals, thus, the emission of CH_4 from cow droppings is greater than that from droppings of other cattle.

The fact that biogas plants use substrates which are often treated as noxious waste, e.g. slaughter waste, makes it possible to utilise them safely, improving sanitary standards. Biogas production also results in a significant reduction of odours released in a great amount during the natural decomposition of animal droppings [35]. These gases are usually removed from biogas by biological desulphurisation, prior to its combustion in a co-generation aggregate.

If the organic waste was to be directly deposited in the environment instead of undergoing fermentation, it could be a source of pathogens causing both human and animal diseases. Most of pathogenic microorganisms are killed by exposure to an increased temperature and such an increased temperature is certain to be found in a fermentation tank.

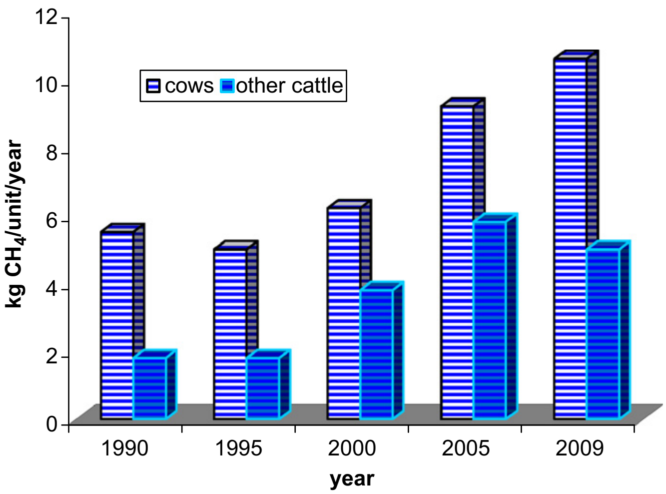

Fig. 5. Indicators of methane emission for cows and other cattle between 1990 and 2009 in Poland, based on [59].

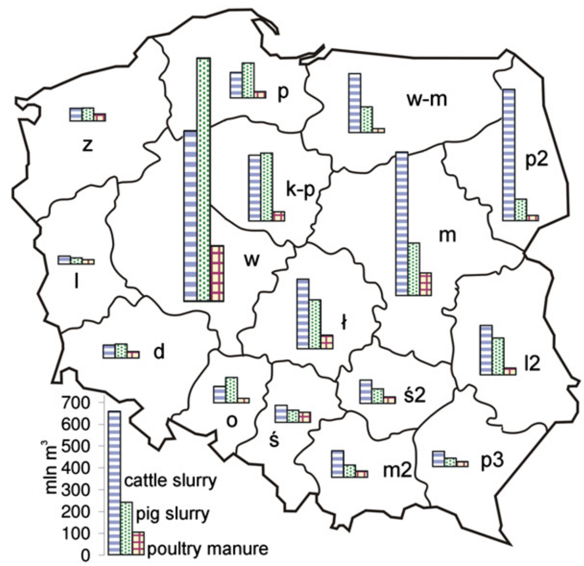

Fig. 6. Theoretical biogas potential in Poland in 2010 for biogas obtained from cattle slurry, pig slurry and poultry manure; voivodeships: z—Zachodnio-Pomorskie, p—Pomorskie, w–m—Warmińsko–Mazurskie, p2—Podlaskie, l—Lubuskie, w—Wielkopolskie, k–p—Kujawsko–Pomorskie, m—Mazowieckie, d—Dolnośląskie, o—Opolskie, ł—Łódzkie, ś—Śląskie, m2—Małopolskie, ś2—Świętokrzyskie, p3—Podkarpackie, and l2—Lubelskie.

The location of biogas plants near prospective customers makes it possible to limit grid energy losses. In addition, creating sources of distributed energy postpones the need to extend transport and distribution grids [60].

6. Agricultural biogas potential in Poland

The farming land takes up about 60% of Poland's area. The vast majority of farming land is taken up by arable land, between 10% and 20% is covered by meadows and pastures and 1% by orchards. The quality of soil is not too high in terms of agricultural use—brown, podzolic and lessive (Luvisols) soils are the dominant types. Fertile soils can be found in the south (Małopolska), Dolny Śląsk, Kujawy and Żuławy Wiślane regions (north of Poland). Poland has favourable climate conditions for agriculture. The vegetation period lasts from about 180 days (north–east of Poland) to 220 days (south–west of Poland) [61].

Wheat is grown in good soils (Małopolska, Dolny Śląsk, Kujawy, Żuławy Wiślane), rye—in central Poland, barley—mostly in the Kujawy region, potatoes—in the central and southern parts of Poland, maize—mainly in the Dolny Śląsk region, sugar beet—in the regions of Kujawy, Dolny Śląsk and in the area of Lublin, fruit and vegetables—in the Mazowsze region and in the vicinity of big cities. The greatest number of cattle is reared in the Mazowieckie Voivodeship and the Wielkopolskie Voivodeship whilst the biggest number of pigs are kept in the Wielkopolskie Voivodeship and Kujawsko–Pomorskie Voivodeship and the biggest number of hens can be found in the Mazowieckie Voivodeship and the Wielkopolskie Voivodeship [61].

The following substances can undergo methane fermentation: farm livestock manure, post-slaughter waste, crops waste, specialist energy plants crops, food waste, glycerol from biodiesel production, etc [62]. Currently, in every Polish biogas plant animal slurry and maize silage constitute the main substrates (Appendix A). These substrates as well as plant waste and an organic fraction of municipal waste will continue to be the primary fermentation substrate in currently constructed and designed agricultural biogas plants in Poland.

Fig. 6 represents the estimated theoretical biogas potential which could have been obtained from cattle slurry, pig slurry and poultry manure in Poland in 2010. Currently, the intensive cow and pig rearing system is a common practice in Poland [63]; the barn production system is still used on individual farms where the number of livestock is limited. The theoretical biogas potential P_t was calculated taking into account conversion factors of livestock heads into Livestock Units *LSU* (500 kg) [64]—for cattle the conversion rate is 0.8, for pigs—0.2, for poultry—0.004. The mean amount of slurry per 1 *LSU* is 44.9 kg for cattle, 43.5 kg for pigs and 26.8 kg for poultry [65]. The number of heads were taken from the data of the Central Statistical Office [66].

$$P_t = 0.365 \cdot LSU \cdot N \cdot A \cdot E_b$$

Where P_t is the theoretical biogas potential, *LSU* is the Livestock Unit, *N* is the number of livestock heads, *A* is the mean amount of slurry produced per LSU in a 24 h period (kg), and E_b is the biogas efficiency from a given slurry (m^3/Mg).

The following voivodeships have the highest biogas potential from animal droppings: Wielkopolskie, Mazowieckie, Kujawsko–Pomorskie and Podlaskie. The total theoretical potential for biogas obtained from slurry is 3646 million m^3 for cattle slurry, 2581 million m^3 for pig slurry and 717 million m^3 for poultry manure. The construction of biogas plants using slurry and/or poultry manure is technically and economically viable on farms with the livestock number of at least 100 heads of cattle, 500 heads of pigs and 5000 heads of poultry [24]. Thus, the technical potential of agricultural biogas from animal slurry in Poland in 2010 should be estimated at 20% of theoretical potential. The technical potential of biogas obtained from cattle slurry is 729 million m^3 (15 PJ), from pig slurry 516 million m^3 (10 PJ), from poultry manure 143 million m^3 (3 PJ) of biogas. The highest number of large livestock farms are located in the central part of Poland (the following voivodeships: Wielkopolskie, Kujawsko–Pomorskie, Łódzkie) and this is where the construction of biogas plants is most viable.

Biogas production which is only based on slurry is relatively low effective, therefore, agricultural biogas plants use biomass of high potential for biogas production [67]—maize is most often used in Poland. In terms of cultivation, maize is characterised by a high crop potential (C4 photosynthesis). Productive varieties of maize are cultivated in Poland and the technology of maize production has been well developed, unlike that of other energy crops such as miscanthus or sorghum.

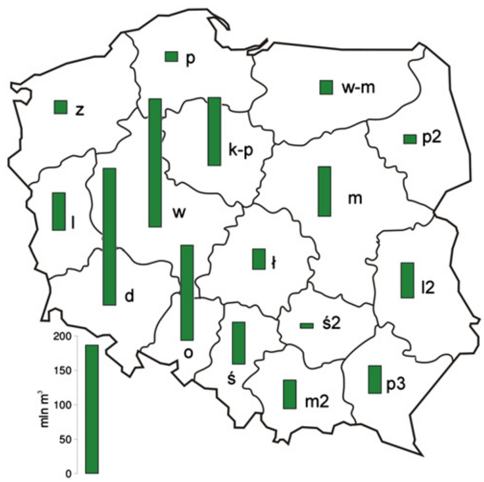

Fig. 7. Theoretical biogas potential in Poland in 2009 obtained from maize silage without the seed.

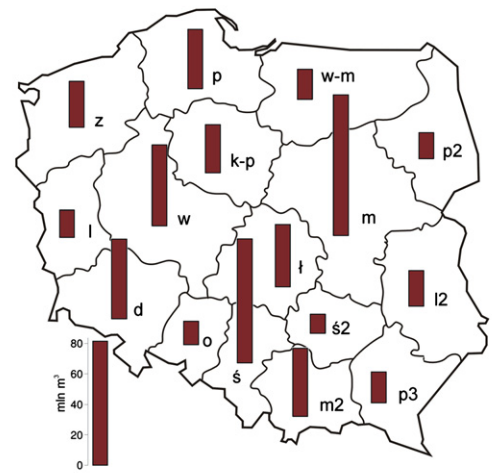

Fig. 8. Theoretical biogas potential in Poland in 2010 obtained from an organic fraction of municipal waste.

In Poland maize is grown for food and to provide fodder for farm animals. After maize cobs have been gathered for food purposes, a mass of stems and leaves is left in the field, which could be used as a biogas production material. Fig. 7 represents the theoretical biogas potential P_t which could have been obtained from food-purpose maize in 2009, provided that gathered seed was 38% of dry mass of the whole plant [68]; the data about crops from particular voivodeship regions was taken from the Central Statistical Office [69].

The following voivodeships have the highest theoretical biogas potential from maize: Wielkopolskie, Dolnośląskie, Opolskie and Kujawsko–Pomorskie. In total, 1044 million m^3 of biogas could be obtained in Poland. Maize silage could be provided to biogas plants by individual farmers, due to which the technical potential is 30% of the theoretical potential, that is, 313 million m^3 (6 PJ).

Due to its vast arable land area as well as fallow and untilled land, Poland has a great potential of designating these parts of land for specialist energy crops used for biogas production. It is estimated that a potential for maize crops in Poland is about 2.0 million ha, that is, three times more than the current crops area. Other arguments for maize cultivation include a small amount of mineral impurities in silage, relatively easy maize ensiling and easy storage as well as its high energy efficiency [70].

The amount of municipal waste produced in individual households and public buildings in Poland reaches about 12 million Mg, of which more than a half is biodegradable waste [71]. Fig. 8 shows the amount of biogas that could be obtained from municipal waste, provided that 50% of waste is a bio-organic fraction. Due to the scattered nature of bio-waste sources as well as a low degree of waste segregation in Poland, the technical biogas potential from municipal waste can be estimated at the level of 10% of the theoretical potential—10 million m^3 of biogas (1 PJ).

In an evaluation prepared for the Ministry of Economy [72] the economic biogas potential in Poland in 2020 was estimated to be 204 PJ, including silage: 81 PJ and waste products: 123 PJ (industrial waste: 26 PJ, agricultural waste: 45 PJ)—in total worth about 6.6×10^9 m^3 of biogas, equivalent to 4.6% of the final energy usage according to the forecast of that time for the domestic demand for final energy.

7. Prospects for the development of agricultural biogas plants in Poland

The rapidly rising prices of traditional energy carriers mean that in the near future a dynamic development of the agricultural

Fig. 9. Agricultural biogas plants under construction in Poland—state as of March 2012 [24,35,73].

biogas sector in Poland is to be expected. The full utilisation of agricultural and food waste products would significantly reduce the import of natural gas [35].

The first biogas plants built in Poland were located next to large livestock farms, mostly due to easily available slurry and a possibility of using electrical power and heat for their own needs. Currently, an increasing number of investors are planning to locate their plants next to agricultural and food industry manufacturers (fruit and vegetable processing, dairies, distilleries) as well as meat producers (slaughter houses, meat processing plants), which would ensure a greater variety of fermentation substrates and a possibility of receiving all-year-round heat produced in cogeneration. The market trends show an increase in the planned power of installed biogas plants. According to the data of the Renewable Energy Institute [24] around 300 biogas plants have been designed and over a dozen will be built in the near future (Fig. 9) [24,35,73].

In 2008 the governmental programme "Secure Energy—Energy Agriculture" was created. As a part of this project, together with non-governmental organisations, it is planned to implement the goal: "A biogas plant in every commune". It is planned that by 2020 over 25,000 biogas plants will have been built, which, according to the Ministry of Economy, would generate power at the level of 3 GW. Bioenergy production, including mainly biogas production based on local resources, is a great chance for the

development and activation of small regions as well as improving self-supply of electrical energy and heat [8,24].

8. Summary

Electrical energy and heat generation from biogas is a source of green, environmentally-friendly energy. At the same time, there is a reduction in methane emission from the decomposition of unmanaged biomass (especially animal droppings) [24,49].

In Poland, there are still many barriers to investing in the construction of biogas plants. These obstacles are also typical of other forms of investment and include legal regulations (a long waiting time for obtaining environmental decisions as well as problems with getting agricultural biogas plants connected to the grid), social arrangements (local inhabitants' unfavorable attitudes towards a biogas plant, mostly resulting from a lack of knowledge of the principles of a biogas plant operation) and difficulties related to a funding source [12,74,75]. The development of the biogas sector in Poland is in its initial stage, the number of specialist companies and qualified specialists, construction businesses and technologists specialising in designing, constructing and exploiting agricultural biogas plants still remains low. Poland is in the phase of creating an institutional and organisation resource base for biogas plants construction, which may cause some inconvenience to investors [35,76].

An obstacle related to the location of investment is a limited ability to receive heat produced in a biogas plant over summer. This problem could be solved by locating an agricultural biogas plant in the vicinity of industrial works which have a constant heat demand throughout the year (e.g. a dairy) or a heat plant. Another benefit of locating an agricultural biogas plant next to an industrial unit generating organic waste is a possibility of obtaining an additional feedstock for biogas production. In Poland it is currently being considered whether to build agricultural biogas plants near the existing natural gas distribution networks and whether to feed biomethane directly to the grid [76–78].

Energy production from agricultural biogas, unlike wind power plants and hydropower plants or solar panels, makes it possible to provide a continuous, uninterrupted energy supply, which is a significant benefit for the electric grid operator and leads to a continuous electrical power and heat supply for rural areas.

Appendix A

See Table A1.

Appendix B

See Table B1.

Table A1
Parameters of materials subjected to fermentation in Poland [5,37–39].

Material	Dry mass content (%)	Dry organic mass content (%)	Biogas efficiency (m^3/Mg of substrate)	CH_4 content (% voulme)
Pig slurry	8	82	50	58
Cattle slurry	10	69	55	55
Pig manure	20	68	55	60
Cattle manure	25	68	65	60
Poultry manure	27	67	140	58
Slaughter waste	5–25	75–95	100–700	55–70
Maize silage without seed	25	85	93	54
Distillery decoction	6–8	83–95	30–50	60
Glycerol	84	91.5	900	60
Sorghum	20	95	105	55
Meadow grass, after flowering	18	90	102	55
Beet leaves silage	15	79	74	56
Potato peel	11	94	73	52
Residue from apple processing	22	97	122	53
Kitchen waste	18	92	90	60

Table B1
Characteristics of agricultural biogas plants in Poland, state as of February 2012 (own development based on [33,34,40–45])

No.	Location	Year of opening	Electrical power (MW)	Thermal power (MW)	Annual biogas production (million m^3)	Annual electrical energy production (GWh/year	Annual heat production [GWh/yr)	Substrates
1.	Pawłówko	2005	0.946	1.101	3.803	7.458	8.680	Slurry, slaughter waste, maize silage, glycerol,
2.	Płaszczyca	2008	0.625	0.680	2.300	4.928	5.361	Slurry, maize silage, plants processing waste,
3.	Kujanki	2008	0.330	0.350	–	–	–	Slurry, plants processing waste,
4.	Kalsk	2009	1.140	1.060	4.500	9.000	8.200	Slurry, maize and sorghum silage,
5.	Koczała	2009	2.126	2.206	8.212	16.761	17.392	Slurry, maize silage
6.	Liszkowo	2009	2.126	1.198	7.400	14.400	8.100	Distillery decoction, plant waste, glycerol,
7.	Niedoradz	2009	0.252	0.291	0.631	1.300	1.500	Poultry manure, slurry, maize silage,
8.	Studzionka	2009	0.030	0.040	0.98	0.18	0.28	Poultry manure, slurry, maize silage, grass
9.	Szewnia	2009	–	–	0.007	–	–	Beetroot and cereal residue, leaves
10.	Kostkowice	2010	0.600	0.608	2.030	4.838	4.903	Manure, slurry, glycerol, food waste,
11.	Nacław	2010	0.625	0.686	2.300	4.928	5.408	Slurry, maize silage,
12.	Świelino	2010	0.625	0.686	2.300	4.928	5.408	Slurry, maize silage, semi-finished products for fodder production,

Table B1 (*continued*)

No.	Location	Year of opening	Electrical power (MW)	Thermal power (MW)	Annual biogas production (million m^3)	Annual electrical energy production (GWh/year	Annual heat production [GWh/yr)	Substrates
13.	Uniechówek	2011	1.063	1.081	4.100	8.381	8.523	Slurry, manure, food, distillery and slaughter waste,
14.	Skrzatusz	2011	0.526	0.505	2.080	4.208	4.040	Distillery decoction, potato waste, carrot waste, slaughter waste,
15.	Grzmiąca	2011	1.600	1.600	6.000	12.800	12.800	Plant and animal production waste
16.	Świdnica	2011	0.900	1.100	4.000	7.200	8.800	Maize silage, grass
17.	Łany Wielkie	2011	0.526	0.540	1.106	4.471	4.625	Distillery decoction, maize silage, manure
18.	Giżyno	2011	1.063	1.081	4.100	8.380	8.520	Slurry, maize silage, glycerol, plant production waste
19.	Uhnin	2011	1.200	1.160	4.500	10.000	9.600	Maize silage, silage of rye, distillery decoction, grass
20.	Mełno	2011	1.360	1.540	5.467	10.522	11.943	Slurry, distillery decoction slurry, beet pulp, maize silage
21.	Siedliszczki	2011	0.999	1.040	3.907	7.876	8.199	Maize silage, whey
22.	Konopnica	2012	1.998	2.128	7.920	15.920	17.024	Maize silage
23.	Zbiersk-Cukrownia	2012	1.600	1.620	4.177	12.800	12.960	Agricultural waste
24.	Boleszyn	2012	1,200	1,220	4.900	9.500	9.600	Maize silage, slurry, distillery decoction, whey

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